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THE COMPARISON OF AIR TRAFFIC CONTROLLERS' TO COLLEGE STUDENTS' MEMORY PERFORMANCE AND BRAIN ACTIVITIES

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We compared controllers and college students memory task performance and brain activities while performing the task. The purpose of these comparisons was to test the hypothesis that controllers must have acquired special memorization skills from many years of air traffic control and that their brains would respond differently from college students' brains. To perform the task, they must maintain a sequence of characters in their working memory and manipulate the characters. We compared controllers' brain activities to college students' recorded at the prefrontal cortex with functional near infrared (fNIR) spectroscopy while performing the task. Our results showed that controllers performed significantly better than college students. Controllers and college students also showed distinctly different brain activity patterns. Controllers used the areas of the prefrontal cortex more evenly than college students. We discuss the implications of the group difference.

To become fully certified, air traffic controllers receive training that usually takes more than three years. As they control air traffic, they monitor and collect the relevant information such as aircraft positions, speeds, altitudes, distances to nearby aircraft, fixes, sector boundaries, and aircraft destination. They must maintain all the information current and integrate them to make safe and efficient decisions. We hypothesized that through many years of air traffic control, air traffic controllers developed skills in memorization, manipulation of memorized information, decision making, and control. The prefrontal cortex executes these functions, and the functional Near InfraRed (fNIR) pad is able to record its activities.

In this paper, we compared controllers of Federal Aviation Administration (FAA) Air Route Traffic Control Centers (ARTCCs; also called en route centers) and college students in their memory task performances and brain activities measured by the fNIR technology. As a performance task, we used a standard memory task, the nBack task (Wikipedia, 2011a). In this memory task, the participants viewed a character presented one by one on the display sequentially and identified a target. In the 0Back condition, the target was always X. In the 1Back condition, the target was the character that was shown previously. In the 2Back task, the participant's target was the character shown two characters previously. In the 3Back condition, the target character was shown three characters previously. The target changed constantly, and the participants needed to hold one, two, and three characters current in their working memory in 1Back, 2Back, and 3Back task conditions, respectively.

Researchers have used fNIR technology to study brain activities for about two decades (Cope, 1991; Ayaz, Izzetoglu, Platek, Bunce, Izzetoglu, Pourrezaei, & Onaral, 2006).The technology uses a pad covering the brain, and the pad has two critical parts: light source and light detector. It sends out light to the cortex of the brain and collects reflected light. From this, it calculates oxygenated and deoxygenated hemoglobin levels in the blood, and these levels are directly related to neuronal activities (Bunce, 2006). Specifically, for neurons to function, they need energy, and this comes from glucose. But they must metabolize glucose with oxygen, which is delivered by hemoglobin molecules in red blood cells. As hemoglobin molecules deliver the oxygen and absorb carbon dioxide, they become deoxygenated and change colors. Although most biological tissues are relatively transparent to light in the red and near-infrared range of the electromagnetic spectrum between 700 nm and 1,000 nm, hemoglobin is a strong absorber of light in this range. By emitting light of two wavelengths (one more sensitive to oxygenated hemoglobin and another more sensitive to deoxygenated hemoglobin) and collecting the reflected light, the fNIR system can calculate changes of their concentrations in the blood over time. From this data, scientists deduce neuronal activities.

Even though we used a standardized simple memory task, nBack, not an air traffic control related task, we predicted controllers would perform better in the task. We predicted that both college students' and controllers' oxygenation levels would increase with the difficulty of NBack tasks. We also predicted that controllers' brains would respond differently from college students', and we would see the different patterns of fNIR data by the different levels of nBack tasks (0back vs. higher level nBack tasks) and by different prefrontal cortex areas. For instance, D'Espito (2001) stated that based on fMRI research results, both ventral and dorsal areas of prefrontal cortex would engage in a simple maintenance tasks, but for high load and complex tasks, the dorsal area would engage more heavily. Accordingly, we hypothesized that fNIR data of the 0Back task where participants would need to maintain the target in working memory and recognize it if displayed would be different from those of more difficult nBack tasks where they must not only maintain characters in their working memory but also switch characters and select the target among them in their working memory. We assumed that for the 0Back task, both dorsal and ventral areas would be involved but for the more complex nBack tasks, the dorsal area would be involved more heavily.

We tested our predictions with memory task performance and fNIR data and discussed the results focusing on the group differences and the fNIR technology as a measure of working memory task performance.

Method

Ayaz, Bunce (now at Penn State), and Izzetoglu ran the experiment at Drexel University and Hah, Willems, and Deshmukh (Hi-Tec contractor for the FAA) ran it at the William J. Hughes Technical Center. We used the same task, materials, software, and procedure.

Participants

Nine college students volunteered to participate in the experiment at Drexel University. Their age range was between 21 and 30 years. Twenty-eight Certified Professional Controllers (CPCs) from en route centers participated as volunteers at William J. Hughes Technical Center, but we analyzed data from 24 participants only because we had a system problem with the first group of four participants. The participants had medical certificates that were current within 30 days prior to their participation in the experiment. Their average age was 44 with a range between 24 and 55 years. They had worked as controllers for 20 years on average with a range between 3 and 30 years.

Materials

fNIR pad.

The fNIR pad (see Figure 1; 6 cm x 16.5 cm x .5 cm; 30 grams) covered the participant's forehead only and had four small light emitting diodes (LEDs) in the middle generating peak wavelengths at 730 nm and 850 nm and 10 light detectors (or sensors) surrounding the LEDs at 2.5 cm apart. Low power light from the diodes shone through the skin of the forehead onto the brain, and sensors recorded the reflection. With this arrangement, we collected data from 16 different places called voxels in the prefrontal cortex at the sampling rate of 2Hz.

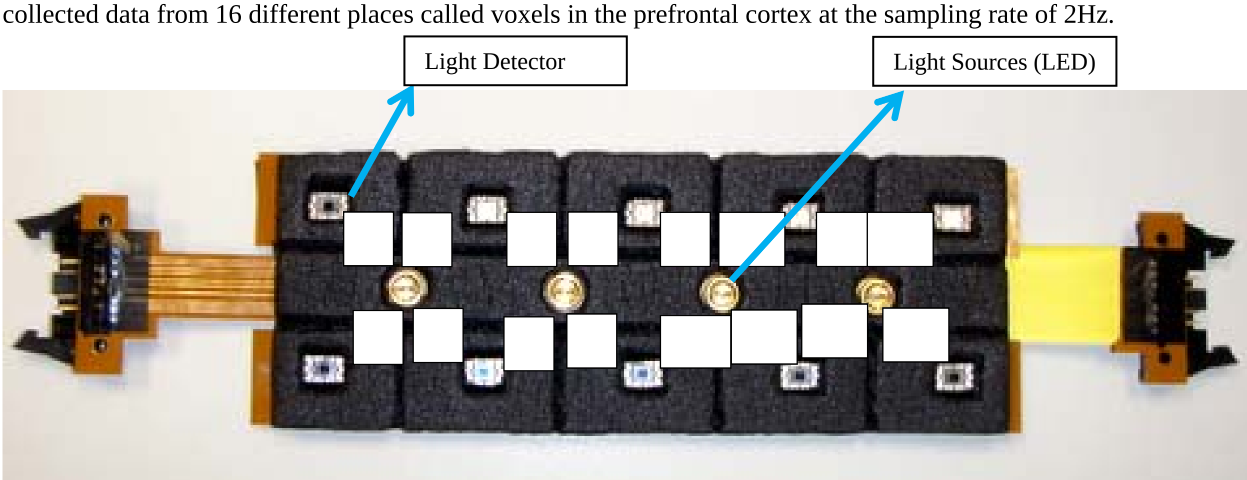

Figure 1. The fNIR pad we used. The numbers represent the schematic locations of voxels in the cortex when it was worn.

The frontal lobe covers about a third of the brain, and the prefrontal cortex encompasses half of the frontal lobe. The prefrontal cortex is responsible for working memory, decision making, strategy generation, and executive functions (Gazzaniga, Ivry, & Mangun, 2002; Gazzaniga, 2004; Saper, Iversen, & Frackowiak, 2000). It connects to perceptual, motor, and limbic areas. It receives projections from wide areas of the brain including the occipital cortex. Even the substructures of the cortex are connected indirectly through thalamic connections. Based on these connections, it controls various brain functions through excitation and inhibition. The fNIR pad is light, small, not-invasive, and portable unlike other technologies such as functional magnetic resonance imaging (fMRI) and electroencephalography (EEG).

Because everyone has different sizes and shapes of the forehead, it is difficult to pin-point which voxel data of the fNIR pad would correspond to which areas of the prefrontal cortex. However, in general we assumed it covered Broadmann areas of 9, 46, 10, 11, 47, 45, and 44 (see Figure 2).

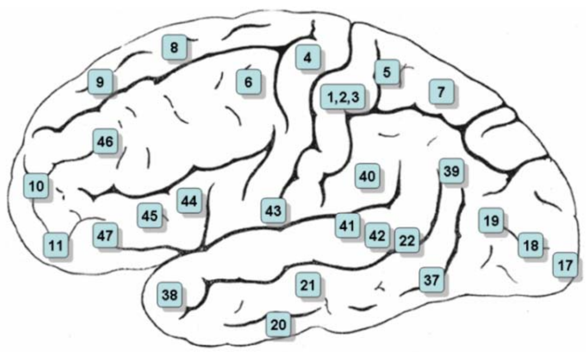

Figure 2. Broadmann map from Wikipedia (Wikipedia, 2011b) (the lateral view of the brain)

nBack memory tasks.

For the memory task, we used four nBack tasks: 0Back, 1Back, 2Back, and 3Back tasks (see Figure 3). The participants viewed a stream of characters displayed on a liquid crystal display (LCD) one by one and responded by pressing the left mouse button for 'yes' if the displayed character was the target. In all nBack tasks except the 0Back task, the target changed as the trial progressed, and the participants must refresh their working memory of the characters. For the 0Back condition, the target was always X, and the participants responded if the displayed character was an X. For the 1Back condition, they needed to hold one character in working memory and decide if the current character was the same as the previous one. For the 2Back condition, they must hold two characters in working memory and decide if the current character was the same as the one shown two characters before. After their decision, they must abandon the oldest one and hold the new two characters in their working memory for the upcoming trial. In the 3Back condition, the target character was three characters before. The participants must always hold the newest three characters in their working memory.

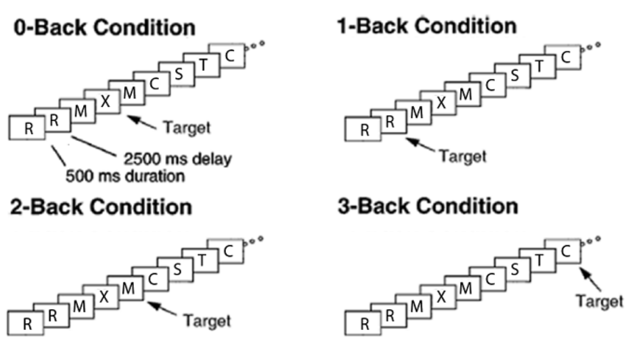

Figure 3. Four nBack tasks showing the target in the sequence.

Procedure

The participants received a short training for all types of nBack tasks before the data collection runs. While they performed the nBack tasks, the participants wore an fNIR pad. They had 28 blocks, that is, 4 nBack types x 7 repetitions that were presented randomly. Each block had 20 trials. For each trial, the participants decided if the character on the display was a target or not. The participants pressed a left mouse button for a target. They did not respond for characters that were not targets. Thus, each participant made 560 decisions. At the start of each block, ‘relax’ was shown on the display for 7.5 sec. Then, which type of nBack trials to be followed such as ‘3back’ was shown on the display for 2.5 sec. Following that display, a stream of characters followed. Each character was displayed for .5 sec with a 2.5 sec interval between characters. This was repeated 20 times. Then, the next run started. The total length of the experiment was just over an hour depending on the speed of the participants’ responses. The sequences of the characters and nBack types were pseudo-randomly presented and were the same for all participants.

Results

We used non-parametric Mann-Whitney U tests using ranks to compare college student and controller nBack performance and brain activities shown in the fNIR data. The controllers performed better than college students with a higher hit rate: 0Back (z = -.4.881, p < .001), 1Back (z =-3.058, p = .002), and 2Back (z = -2.008, p = .045). There was no group performance difference for the 3Back. For the false alarm rate, there was no performance difference between them for any of the nBack tasks. Hit rates declined and false alarm rates rose as the number of characters to be remembered increased. The error bar in Figures 4 and 5 represents one standard error.

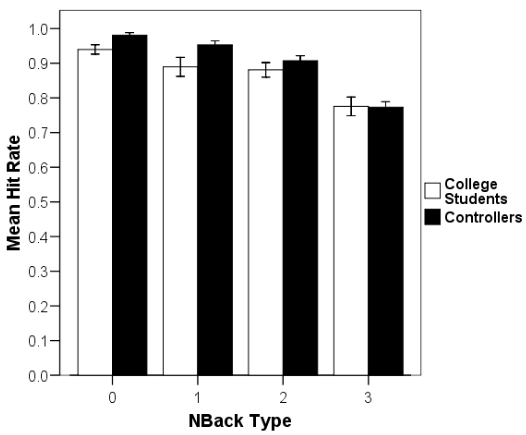

Figure 4. Hit rates by nBack types.

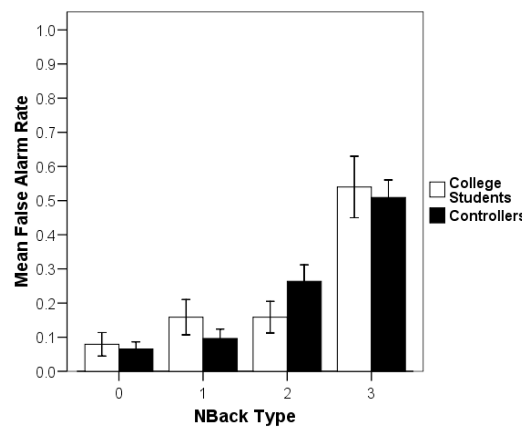

Figure 5. False alarm rates by nBack types.

Controller brain activities shown in the fNIR data were more even across voxels for all NBack tasks than college student brain activities (see Figure 6). Also, as shown in the 0Back figure, controller fNIR levels were generally higher than college student levels. We considered 0Back task as the baseline task.

Since controllers had more heightened oxygenation levels for the baseline (0Back) than college students, it was not meaningful to compare their oxygenation levels with college students’ levels directly at different nBack task conditions. We decided to compare college students’ to controllers’ incremental effort as the task became more difficult. We subtracted 0Back oxygenation levels from 1Back, 2Back, and 3Back oxygenation levels for each group, respectively. In general, college students’ incremental effort was larger than controllers’ in all nBack tasks. To test this statistically, we averaged increases of individuals at each voxel for each group. Then, we compared two groups across 16 voxels for each of (*NBack – 0Back*) separately using Mann-Whitney U tests. The results showed college students exerted more effort than controllers for *1Back-0Back* (z = -3.279, p = .001) and *2Back-0Back* (z = -4.033, p < .001). The difference at *3Back-0Back* between the two groups was not significant.

Because the fMRI research results showed the different roles of dorsal and ventral areas of prefrontal cortex (D’Espito, 2001), we examined if there would be different oxygenation patterns collected from the upper and lower parts of the pad . The upper part represented voxels 1, 3, 5, 7, 9, 11, 13, and 15. The lower part represented the rest of the voxels. We assumed the upper part would receive responses from the dorsal areas mostly and the lower part would receive responses from the ventral areas mostly. Figure 7 shows the differential oxygenation levels at the upper and at the lower parts of the pad. The results did not show the expected trend, that is, there was no trend of higher oxygenation at the dorsal area for more difficult nBack tasks.

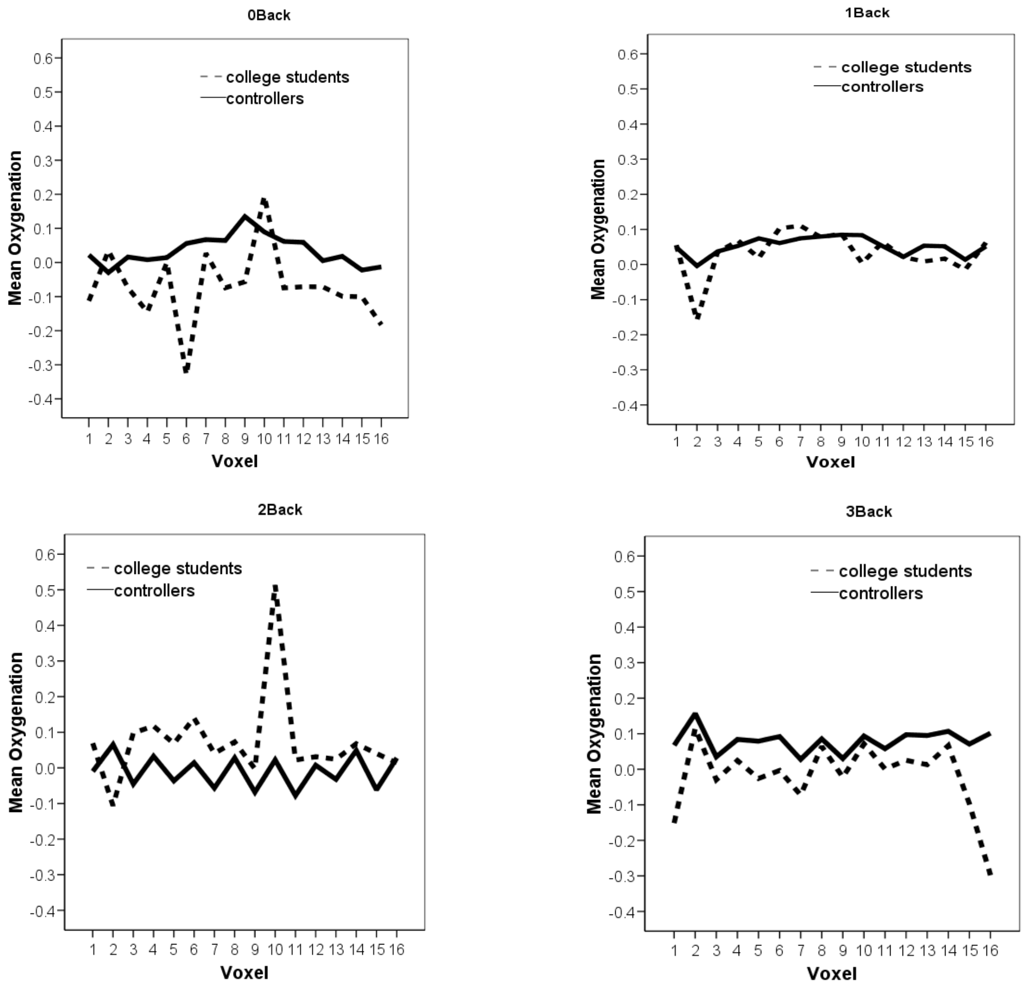

Figure 6. Mean oxygenations at voxels by different NBack tasks of college students and controllers.

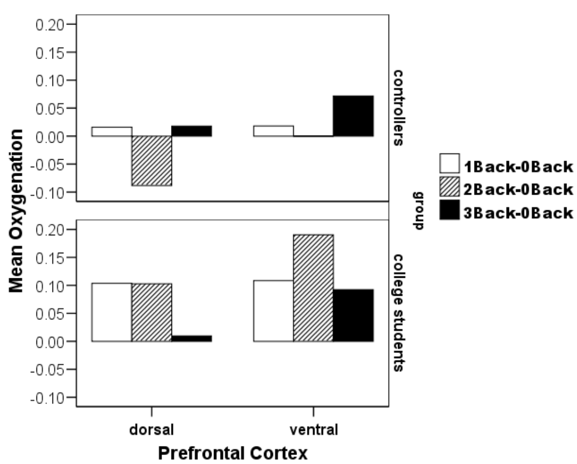

Figure 7. Oxygenation levels at dorsal and ventral areas for (1Back-0Back), (2Back-0Back), and (3Back-0Back) tasks of college students and controllers.

Discussion

We compared controllers and college students memory task performance and their brain activities. Our experimental results showed the controllers performed better in all nBack tasks except the 3Back task. We assumed the controllers must have acquired skills relevant to memory tasks in their job. In the 3Back task, both groups did not perform well. Their hit rates were below 80%, and noise in the data might have contributed to the failure of revealing the groups' difference. Their false alarm rates were also close to 50% in the 3Back task.

We expected that oxygenation measured by fNIR would be higher with more difficult NBack tasks. But our results did not support it. We also expected that the contribution of the dorsolateral prefrontal cortex would increase with the difficulty of the nBack tasks because the participants must manipulate characters in their working memory in addition to maintaining them in the high-level nBack tasks. Our results did not support this either. One possible reason is that to perform the nBack tasks, the participants might have used other parts of the brain extensively, which our fNIR pad did not cover, and the role of the prefrontal cortex may not be that significant. However, our fNIR data showed controllers spent less incremental effort than college students as the difficulty of the nBack tasks increased. As Posner and Raichle (1997, p. 244) mentioned, more repetitions (that is, higher skills) lead to less effort. This particular result is in line with the performance results that controllers performed better than college students.

It was intriguing to find in our fNIR data that the controllers responded evenly across the prefrontal cortex in contrast to college students. This needs further research such as the effect of aging, but it may imply that controllers have used all parts of the prefrontal cortex for all of the nBack tasks. This may implicate that their frontal cortex had developed a tight and well-connected organization, and one part may be closely linked to the other parts of the prefrontal cortex. Since they exhibited superior performance over college students, we conjecture that the presumed tightly organized prefrontal cortex like our controllers may be a developed form of the prefrontal cortex in performing memory tasks such as nBack tasks. This has a very significant implication in training and system designs. When researchers devise training methods and systems, they use results of the past research that used ordinary adults as the participants, not necessarily the skilled and domain specific adults such as air traffic controllers. We conjecture that some assumptions of human capabilities and limitations known to us may not be applicable to skilled populations such as air traffic controllers.

Acknowledgement

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